Performance and emissions of natural gas fueled internal combustion engine:
A review

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Natural gas, referred to as green fuel, has emerged as a solution to depleting crude oil resources as well as to the deteriorating urban air quality problem. As a gaseous fuel, gains from natural gas have already been established in terms of low emissions of carbon monoxide, hydrocarbon and particulate matter. Air-fuel ratio, operating cylinder pressure, fuel injection, and compression ratio are some of the parameters that need to be analyzed and optimally exploited for better engine performance and reduced emissions. In this study, a comprehensive review of various operating parameters and concerns have been prepared for better understanding of operating conditions (spark and compression ignited engines) and constrains for a natural gas fueled internal combustion engine.

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Introduction

Air pollution is fast becoming a serious urban as well as global problem with the increasing population and its subsequent demands. This has resulted in an increased interest in using natural gas (NG) as fuel for internal combustion (IC) engines. NG resources are vast and widespread geographically and are not limited to politically sensitive locations as is typical for crude oil. Based on current consumption rates, the estimated total, recoverable gas, including proven reserves, is adequate for almost 200 years. To benefit from the use of NG in IC engines, it is necessary to understand its combustion under the appropriate conditions and to study the effects of various parameters on it. This review aims to prepare a concise state of art that provides an idea of various concerns related to employment of Compressed Natural Gas (CNG) as a vehicular fuel in order to improve the rapidly deteriorating air quality conditions in urban regions.

There are two basic types of engines used in vehicles- the spark ignition (SI) or gasoline engines and the compression ignition (CI) or diesel engine. Diesel engines tend to be more energy efficient than gasoline engines, provide higher torque output and operate over limited engine speeds; however, such engines typically do not provide the throttle response and flexibility desired for lighter weight vehicles. The parameters of particular interest are engine torque, power and specific fuel economy. The actual power output of an engine depends on the ambient air temperature and pressure in the test cell. These engine performance characteristics affect driving techniques and fuel economy.

Engines are basically air pumps. For more power, an engine must burn more fuel; hence more air must be pumped into the cylinders. The amount of air available to the engine depends on the resistance to flow through the engine intake system, cylinder and exhaust system. The ability of an engine to pump air is called volumetric efficiency (VE), which if reduced; the maximum power output will be reduced in a similar manner. Liquid fuel when atomized, generally consumes very small space in the intake system, thus do not affect VE significantly. While gaseous fuels require 4 to 15 percent of intake passage volume. Space occupied by the fuel reduces the amount of air entering the engine; hence the power output of the engine is reduced. Theoretically, loss in power output for LPG (4%) is less than NG (9.5%).

Liquid fuels vaporize manifold as they mix with air in the engine’s intake and then enter the cylinders. This vaporization absorbs energy and cools the

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higher ignition temperature, CNG is less hazardous fuel than any other petroleum based fuel. The higher octane rating (120) for NG as compared to that of gasoline (87) allows a higher CR (15:6:1) and consequently more efficient fuel consumption. Due to higher CR, CI engines can also use CNG as a fuel. But since cetane rating for CNG is poor, it cannot replace diesel totally like gasoline.

Maintenance cost for gaseous fuel is lower than that for gasoline or diesel engine, because gaseous fuels burn clean without carbon deposits. Furthermore, in gas engines, the fuel does not mix up with the lubricants to dilute it or reduce its viscosity so that lubricant consumption is lower in gas engines than that of gasoline or diesel engines. Optimized natural gas vehicles are expected to produce less carbon monoxide near-zero reactivity of methane, and may cause less ozone formation than gasoline and diesel engines.

Types of Natural Gas Engines

NG combustion is characterized by a long ignition time delay\textsuperscript{1–4} and cannot be used directly as a fuel for an IC engine using compression ignition (diesel cycle). Hence, some type of ignition aid is required. Dual fuel (DF) is one practical way to use NG in such engines.

Now a days two types of NG engines are primarily studied: I) A dual diesel engine using homogeneous NG mixture and diesel fuel spray. It needs two fuel supply systems and still has problem with high HC emissions. II) A homogeneous SI engine has problems with low power output and combustion instability under lean-burn condition. In a CNG and Diesel DF operation, NG is inducted into the cylinder in gaseous state and diesel is injected prior to the TDC of compression stroke. After a short ignition delay, the combustion of diesel occurs first, igniting the NG and then flame progression begins. Hence combustion of CNG/diesel DF engine has combined characteristics of CI and SI engines. According to engine control strategies under very low load operating conditions, the DF engine runs on pure diesel process, which can be divided into four phases of compression, combustion, expansion and exhaust.

Gaseous fuels are more suitable for higher compression engines since they resist knock more than conventional liquid fuels (due to high octane value that permits a high compression ratio, leading to higher thermal efficiency at full-load condition) as well as produce less polluting exhaust gases, if appropriate conditions are satisfied for their mixing...
and combustion. Therefore, it is more economical and of environmental advantage to use NG in diesel DF engines.

Traditional premixed charge combustion engine has lower thermal efficiency due to high occurrence of engine knock and the unavoidable throttling at intake. Homogeneous-charge lean combustion engines can realize a high thermal efficiency due to the low pumping and heat loss and increase in the specific heat ratio, at the expense of moderately high NOx emissions due to ineffectiveness of the catalyst. However, the lean operation limit for this type of lean homogeneous engine was not high compared to the value of diesel engine. The charge stratification in the combustion chamber permits extremely lean combustion that increases the thermal efficiency but gives the penalty of high NOx and even particulate emissions.

Noise, produced by the combustion process, may have direct effect on observers. It may cause immediate annoyance and physiological change. Combustion noise occurs in two forms, direct and indirect. Direct noise is generated in and radiated from a region undergoing turbulent combustion. The indirect noise is generated downstream of the combustion region due to interactions between streamlines of different temperatures. In diesel engines, both the pressure–time form and the turbulence–combustion interaction may be important to the noise problem. Diesel engine produces more noise than that produced by SI engine. Main factor that affects the combustion noise is the pressure rise rate during combustion. The combustion noise data for DF engine that utilizes diesel as pilot fuel and gaseous fuel is lacking.

**Present Status of Natural Gas Engines**

In an experimental study on combustion characteristics of a turbo charged NG and diesel duel-fuelled CI engine, ignition delays, and effects of pilot diesel and engine load on combustion characteristics were analyzed using measured cylinder pressures of the engine. Under low-speed and low-load operating conditions, the rate of pressure rise was observed rather high. HC and CO emissions increase with increase in methane concentration (load). An increase in pilot diesel can extend the lean burning limit and decrease HC and CO emissions but has opposite effect on NOx emissions. With the same amount of pilot diesel, ignition delay changes irregularly when loaded or the concentration of NG increases, especially under medium-load condition. NOx may reach a high level owing to some engine maladjustments. When a DF engine runs under low-load conditions, the exhaust is always smokeless. Even if it is operated at full-load condition, smoke is still less than that from diesel engine.

Experimental work to study the combustion characteristics of NG direct injection (DI) combustion under various fuel injection timings by using a Rapid Compression Machine (RCM) showed that natural gas DI can result in combustion that is faster than homogeneous combustion while shortening the time interval between injection timing can markedly decrease the combustion duration. The unburned HC concentration would increase over a wide range of equivalence ratio (ER). Shortening the time interval between injection timing and ignition timing can decrease the value to that of homogeneous–mixture combustion. The NOx level is high but the CO level remains low over a wide range of ER and a little affect by the variation in fuel injection timing. Natural gas DI combustion can achieve high combustion efficiency as that of homogeneous-mixture and does not deteriorate over a wide range of ignition timing.

In a corresponding study on the combustion behavior of CNG in DI, spark-ignited RCM found out that CNG direct combustion realizes shorter combustion duration than that of homogeneous mixture combustion. This is caused by both mixture stratification and gas flow produced by fuel jet. The pressure rise caused by combustion and heat release pattern shows reasonable consistency in this behavior of combustion duration. Also, CNG direct injection combustion maintains the combustion efficiency at more than 0.92 of ER range (0.1-0.9). Combustion efficiency deteriorates at very low ER due to bulk quenching and at high ER due to excessive charge stratification.

A study was undertaken as to how a pilot injection of diesel fuel affects the combustion of NG–air mixture in an environment approximating that of a diesel cycle. After calibration of a 3D numerical model by combustion bomb tests, parametric studies were carried on the pilot injection pressures and the number and size of nozzles holes for a fixed diesel fuel flow rate. The numerical model gave a very good agreement with experimental results in predicing the combustion pressure. However, at the tail of the burning period,
the experimental results fall more rapidly than those of the simulation. Also, when the injection pressure increases (20-60 Mpa), the combustion pressure increases (30%) at about 40 min after injection. The higher fuel injection pressure gives a faster combustion of NG. The results show that a high injection pressure has the beneficial effect of increasing the performance of DF combustion. For the same mass flow rate of diesel fuel, an increased number of holes of smaller diam increase the early, premixed combustion due to better fuel distribution and fuel vaporization. The rate of burning of the NG is enhanced because the larger number of ignition centers from the pilot diesel fuel are distributed more widely throughout the chamber. As a result, the performance of the dual fuel combustion improves.

Noise Pollution

In a study on the noise pollution and combustion pressure for a DF engine running on diesel and CNG, the maximum pressure rise rate during combustion is presented as a measure of combustion noise. A Ricardo E6 diesel version engine, converted to run on dual fuel of diesel and CNG, has been used throughout the work. The engine is fully computerized and the cylinder pressure data and crank angle data are stored in a PC for off-line analysis. The effect of engine speeds, loads, pilot injection angle, and pilot fuel quantity on combustion noise is examined for both diesel and dual engine. The combustion noise is represented by the maximum rate of pressure rise during combustion. From the experiments and results presented, the following conclusions were drawn:

1. Combustion noise decreased with increasing the engine speed for diesel and DF engine. Also, at all engine speeds, DF engine produced a higher-pressure rise rate than that for diesel.
2. At constant engine speed, increasing the load did not affect the combustion noise much for the diesel engine. However, for the DF engine increasing the load resulted in severe increase in combustion noise, which was higher than those for the diesel case.
3. Maximum rate of pressure rise for diesel engine occurred before TDC, while for DF engine, it occurred at a later crank angle, after TDC. Also, for the DF engine, at constant engine speed, the maximum cylinder pressure is higher than that for the diesel case, at all loads.
4. Increase in diesel fuel injection advance results in an increase in the combustion noise. Also, it is higher for the DF engine than for diesel.
5. For the DF engine, increasing the mass of pilot fuel mass injected, results in a decrease in combustion noise up to certain value then it starts again to increase. Engine torque increased with increasing the pilot fuel mass. At a specific pilot fuel mass, the maximum pressure rise rate and the maximum pressure were minimum.

Air Pollution

A study for CNG fueled vehicles on emission testing has shown that formaldehyde level for CNG vehicles are generally equivalent or less than formaldehyde levels for gasoline fuels. In terms of efficiency, performance and range study, DF vehicles suffer a major drawback either in terms of efficiency or acceleration performance. In all cases studied, CNG energy economy was lower than EPA certification fuel economy data for the pre-conversion gasoline vehicle (i.e. conversion appears to have reduced efficiency on gasoline). All the vehicles tested by EPA also yielded large decrease in acceleration performance, measured by 5 - 60 mph and 30 – 60 mph. Finally, each of these DF vehicles had a lower range on CNG than on gasoline, typically at least at a 50 percent reduction. It has been estimated that current CNG storage tanks only provide one-sixth of the range of an equivalent sized gasoline tank. These concerns make reliance on CNG dual fuel vehicle as an air quality strategy very problematic. Efficiency, performance and range characteristics can be improved with dedicated and optimized CNG vehicles.

Using accepted relationship between weight, acceleration and fuel economy, it was estimated that a CNG with range and power equivalent to the gasoline model would be less efficient (25%). This tradeoff between efficiency, performance and range is the reason why many experts believe CNG is better suited for centralized urban fleet applications than for general public use. The study finally concluded that CNG dual fuel retrofitted vehicle could provide very large CO reduction (80-95%) compared to current gasoline vehicles. The NMHC and NOx emission impacts can vary greatly depend on conversion. Emission benefits available from CNG would be greater in dedicated vehicle optimized for individual alternative fuel.
Experiments\textsuperscript{15} at IIT Delhi in developing a CNG fuelled SI engine have shown that the maximum level of CO emission was 0.325 percent, NOx emission concentration achieve the peak value around an ER of 1.1. Results showed an improvement in the performance and emission characteristics of CNG fueled engines using specially designed Electro Mechanical Fuel system.

A study\textsuperscript{16} of NG, using a single cylinder, a multi cylinder engine and six vehicles, showed that the light-load lean-limit misfire region of NG begins at an air fuel ratio between 140-150 percent of stoichiometric value. Changes in ignition timing, significantly influenced emission of NOx and HC but had little effect on CO emissions. Lower emissions can be achieved (by adjustment) with current design engines, but with heavy penalty to engine performance. Emissions from vehicles fueled with NG are virtually unaffected between –6 to 38°C. NG exhaust are estimated to be 22-25 percent as reactive as gasoline exhaust. The CNG fueled engine\textsuperscript{17} showed improved efficiency (3-5 %) depending on the CR and air index and emitted less CO but slightly higher amount of NOx.

Conclusions

SI engines can be operated with CNG in place of petrol. In IC engines, compression ignition requires an ignition aid (DF utility) due to its characteristic of ignition time delay. NG has higher octane number than petrol and therefore permits higher CR that helps in resisting knocking and throttle at intake. Homogeneous-charge lean combustion engines lower pumping and heat losses, which in-turn increases the specific heat ratio and that can realize a high thermal efficiency but at the expense of moderately high NOx and PM emissions. In a DF engine, an increase in pilot diesel can extend the lean burning limit and decrease HC and CO emission but has opposite effect on NOx emissions. In low-load condition for a DF engine, the exhaust is always smokeless; even in case of full-load condition, smoke is still less than that from diesel engine. CNG direct combustion realizes shorter combustion duration than that of homogeneous mixture combustion. Natural gas DI combustion can achieve high combustion efficiency as that of homogeneous-mixture. NOx level is high but the CO level remains low. As the injection pressure increases, the combustion pressure increases. The higher fuel injection pressure gives a faster combustion of the natural gas. The results show that a high injection pressure has the beneficial effect of increasing the performance of DF combustion. The combustion noise decreased with increasing the engine speed for the diesel and the DF engine. At constant engine speed, the maximum cylinder pressure is higher for DF engine than that for the diesel case, at all loads. Generally, the DF engine exhibited higher rate of pressure as compared to diesel engine. CNG dual fuel retrofitted vehicle provides large CO reduction (80-95 %) compared to gasoline vehicles. The emission impacts of NMHC and NOx can vary greatly depending on conversion. Greater emission benefits from CNG could be realized in a dedicated vehicle optimized for individual alternative fuel. Changes in ignition timing significantly influenced emission of NOx and HCs but had little effect on CO emissions.

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